Predictability Limitations Of Long-Range Sound Propagation

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LONG-TERM GOALS

To determine the predictability limitations of acoustic signals in long-range propagation. The effects of short-wavelength mesoscale structure are examined from the ray and wave chaos points of view at megameter ranges, and is shallow water the effects of bathymetric variability are examined from the ray and wave points of view at ranges of many tens of kilometers. Finite frequency effects and measurement techniques for the experimental observation of "wave chaos" in the ocean are emphasized.

OBJECTIVES

The full-wave UMPE (University of Miami Parabolic Equation) acoustic model is used to study propagation, forward scattering and backscattering of sound waves by volume, surface, bottom and sub-bottom inhomogeneities in order to quantify the limits of predictability of broadband signals in realistic 3-D laterally variable ocean environments.

APPROACH

The full-physics acoustic model called UMPE is used to predict broadband signal propagation, forward scattering and backscattering. Standard data bases are used for the background, and superimposed are fields of internal waves, mesoscale structures, surface roughness, bottom and sub-bottom roughness, and other features such as compact and distributed targets. Limitations of predictability are studied by simulations under varying oceanic conditions in order to obtain estimates of the means and variances of the quantities that are predicted as functions of range and frequency: CW and broadband transmission losses, reverberation levels, travel times and coherence times, noise levels, power fluctuations and so forth. In some cases, analytic theories relating to chaos in dynamical systems are developed to explain the extreme sensitivity of the predictions to small perturbations.

WORK COMPLETED

Full-wave numerical simulations of internal wave scattering of sound in shallow water are performed with an efficient broadband PE/SSF model that also includes scattering by bathymetric variations. Bathymetric scattering by itself gives an exponentially large number of unresolvable multipaths as predicted by ray chaos theory. When internal waves that evolve dynamically in geophysical time are included, the unresolvable multipaths are found to be temporally unstable with coherence times less than a few minutes at ranges greater than a few tens of water depths in shallow water, except possibly for rare paths that are shielded from internal waves such as within strong surface ducts. Comparisons to measured acoustic data in the Straits of Florida yield excellent agreement.[1]

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Full-wave numerical simulations of sound propagation in deep water to megameter ranges are performed with the same efficient broadband PE/SSF model. The ocean environment includes a broad spectrum of mesoscale structure that causes a "mesoscale bias" in the travel time of the late axial arrival and significant mode coupling of the near-axial waves that may be interpreted as chaos. Since this chaos occurs in finite-frequency numerical simulations, it may be called "wave chaos" to distinguish it from the familiar "ray chaos" that occurs in ray-based numerical models.

RESULTS

An example of a recent result concerns explosive beam spreading due to ray chaos.[2] A numerical simulation of chaos at finite frequency, called "wave chaos," is displayed in the figure below. A source with Gaussian beam pattern having rms angle of 0.5 degrees and center angle 0.0 degrees is placed at zero range and depth 200 m in deep water that has a typical sound speed profile. The water depth is 4000 m, the sediment thickness is 200 m, and the source frequency is 400 Hz. The upper panel shows the output from a PE run when no mesoscale structure is present and the problem is range-independent. In the plots, the azimuthal spreading term has been removed to decrease the dynamic range of the plots. In accordance with conventional theory, the beam is seen to spread linearly with range. The lower panel shows the result when strong mesoscale structure is present. In this case the beam is seen to spread exponentially, i.e. explosively, with range. Before the range 1000 km, the beam completely fills the water column.

A comprehensive theory of this phenomenon has been worked out.[1] The theory demonstrates that the rate of the exponential growth of the beam width is precisely the Lyapunov exponent of the unstable, chaotic ray at the center of the beam that can be calculated on the basis of the variational equations of geometrical acoustics. When the beam width becomes comparable to the water depth, then the exponential growth saturates because the beam cannot spread any farther. Thus "wave chaos" is a transient phenomenon that might be observed in the ocean with very narrow beams.

IMPACT/APPLICATIONS

Traditional travel-time ocean acoustic tomography requires many stable, resolvable and identifiable paths, conditions that are not satisfied in shallow water at longer ranges or in deep water at multi-megameter ranges for most of the energy carrying near-axial rays. Some other inversion method will have to be developed for remote sensing of shallow water environments and basin scale deep water environments. It is suggested that a full-wave inversion method that uses all of the information in the waveform of broadband signals, and not just ray travel times, would provide more robust results.

TRANSITIONS

Especially in shallow water environments, the one-way UMPE model with multiple forward scattering, and the two-way UMPE reverberation model, offer considerable improvements to the U.S. Navy for ASW applications.

RELATED PROJECTS

PE/SSF: K. B. Smith, Naval Postgraduate School
CHAOS: M. G. Brown, University of Miami, and other members of the ONR-sponsored group on "Chaos and Predictability in Ocean Acoustics."

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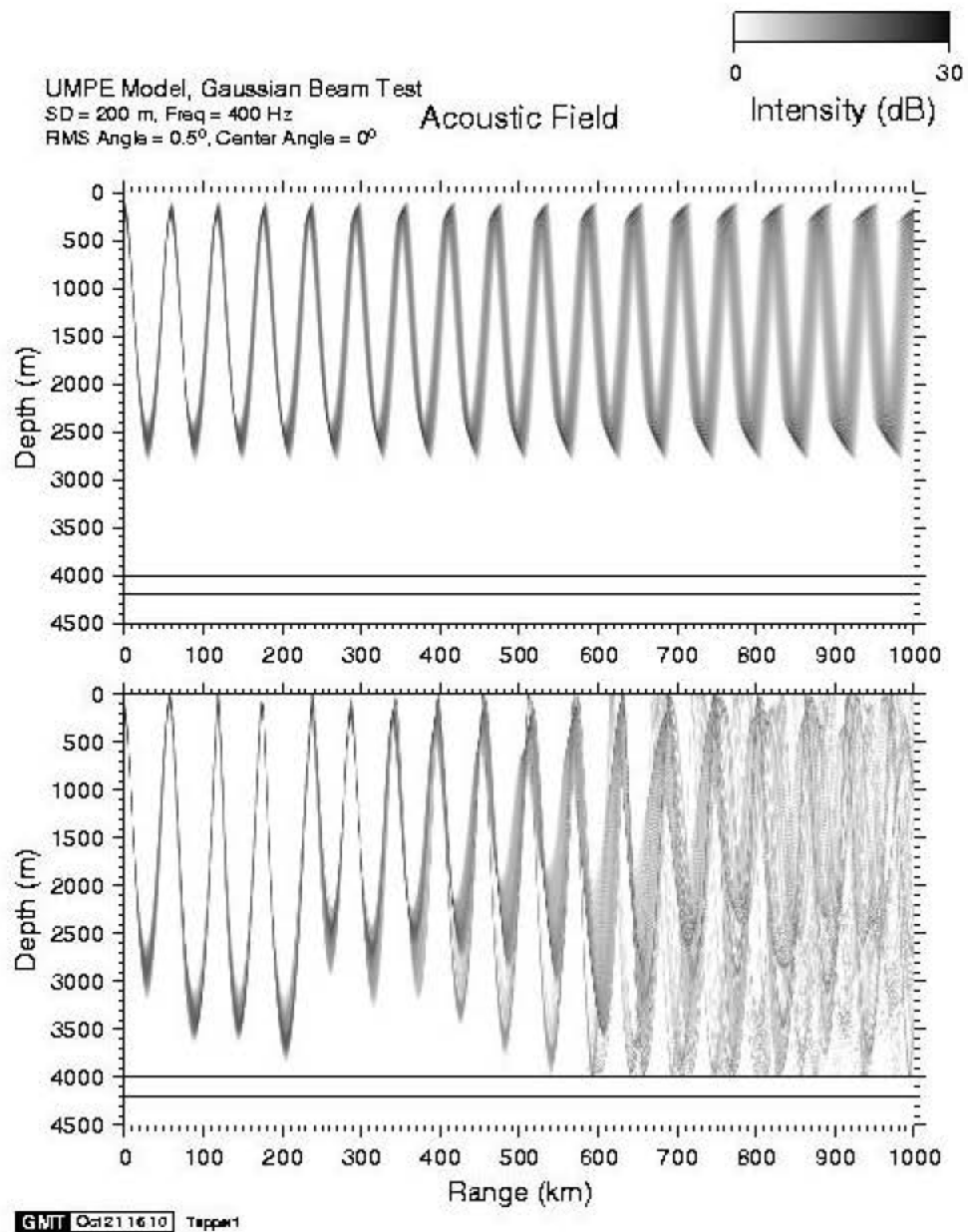
FIGURE 1. Exploding beam. An example of wave chaos